Performance-related characterization of fluidized thermal backfills containing recycled components

PERFORMANCE-RELATED CHARACTERIZATION OF FLUIDIZED THERMAL BACKFILLS CONTAINING RECYCLED COMPONENTS

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ABSTRACT

The investigation described in this paper focused on the performance-related characterization of cementitious Fluidized Thermal Backfills (FTBs) containing recycled components derived from pavement maintenance and aggregate or stone processing operations. In particular, the study was performed with the purpose of assessing the suitability of these peculiar mixes in situations which require the filling of cavities in the presence of several conduits with high-voltage transmission cables.

FTBs were prepared in the laboratory by modifying their standard composition in order to include variable percentages of Reclaimed Asphalt Pavement (RAP) and of three different types of mineral sludge. Components were subjected to preliminary physical characterization and the sludges were investigated in detail with the purpose of identifying their microstructure and chemical composition. In consideration of their intended end-use, FTBs were characterized in terms of their flowability, thermal conductivity and thermal stability. Furthermore, while considering a typical layout of high-voltage cables, an analysis was carried out in order to quantitatively assess the influence of FTB composition and characteristics on line ampacity.

Results showed that FTBs may be successfully designed to include recycled components while still retaining satisfactory flow characteristics and thermal properties, although it should be considered that they are extremely sensitive to variations in composition. Furthermore, it was proven that the considered FTBs all led to a satisfactory line ampacity and that in fact their formulation may be adjusted to improve the durability of high-voltage cables.

Statement of novelty

The findings illustrated in this paper are extremely relevant in the context of waste management since they prove that the use of Reclaimed Asphalt Pavement (RAP) and mineral sludge in Fluidized Thermal Backfills (FTBs) constitutes a valuable alternative to landfilling, with the corresponding valorization of waste materials that are usually available in significant amounts. It should be underlined that no similar studies were found in the technical literature on fluid cementitious composites. It is envisioned that the obtained results may be of value for the design and production of FTBs with other recycled components, provided that a similar assessment is carried out with respect to the most important performance-related properties.

Keywords: Fluidized Thermal Backfill, Reclaimed Asphalt Pavement, mineral sludge, flowability, thermal conductivity, ampacity

1. INTRODUCTION

The construction of new tunnels and road networks is often combined with the placement of utility lines such as high-voltage transmission cables which in most cases are buried underground to ensure safe and reliable power transfer. Their current carrying capacity depends on several factors, among which temperature of the conductor plays a crucial role. Hence, heat dissipation capacity of the material surrounding cables should be ensured by employing the so-called thermal backfills [1-4]. If needed, these can be designed as Fluidized Thermal Backfills (FTBs), which are self-levelling and self-compacting flowable mixes constituted by a proper combination of hydraulic binder, aggregates, fly ash and water [5-7]. Their formulation can be adjusted to include several recycled components which contribute to the reduction of costs and environmental impact associated to construction operations [4, 5, 8].

FTBs are significantly different from conventional backfill materials like soils [9-11] due to their pumpability, improved thermal conductivity and remarkable thermal stability. The latter aspect is of special relevance since it refers to the capability of the material to guarantee constant thermal properties despite drying phenomena which may occur in proximity of the cables as a result of their high in-service temperature [5, 10]. Although mechanical properties of FTBs may vary significantly depending upon project-specific configurations and needs, their stiffness and strength need to be sufficient for the protection of buried cables from the effects of traffic loads. However, limitations to the maximum strength achieved in long-term conditions are frequently introduced as additional design requirements in order to facilitate the removal of such materials in the case of post-construction maintenance operations. As a consequence, FTBs with such characteristics belong to the wider category of Controlled Low Strength Materials (CLSMs) which are employed in several civil engineering applications [12].

Recycled materials used in this study for the formulation of FTBs are Recycled Asphalt Pavement (RAP) and mineral sludge. Both are typically available in abundant quantities and they are usually treated either as waste materials, to be transported to landfills, or as potentially recyclable materials, for which adequate technological solutions need to be sought depending upon the intended end-use.

RAP is produced by the milling of the surface courses of road pavements which are constituted by bituminous mixes. These are removed from existing infrastructures as part of periodical resurfacing, rehabilitation or reconstruction operations in order to meet given serviceability requirements. The generated waste material, referred to as RAP, is granular in nature and is formed by aggregates coated with aged asphalt binder. As per the recent estimates, in Italy 30% of available RAP is disposed of in landfills [13]. However, RAP is also used as replacement of virgin aggregates in bituminous mixtures [14-15], provided that it is adequately granulated and fractionated before use. Such a practice is encouraged by the fact that as part of the Long-Term Pavement Performance (LTPP) program of the Federal Highway Administration, it has been reported that pavement bitumen-bound layers with up to 30% RAP exhibit a performance which is equivalent or better than that of standard bituminous layers containing exclusively virgin materials [16]. Several other studies have shown that it is possible to reuse RAP in the construction of pavement granular bases or subbases [17-18] and that combinations of RAP and virgin aggregates stabilized with cement can also be employed in road base construction [19]. RAP has also been used as a replacement of coarse aggregate in cement concrete: however, outcomes of investigations and trials indicate that such a practice should be limited only to non-structural applications due to the difficulty in achieving high strength [20].

In conclusion, use of RAP in construction materials has been investigated widely and in general it has been found that it leads to a reduction of construction costs, depletion of virgin aggregates, land-filling and energy consumption. However, there are no studies that document the use of RAP in FTBs, probably as a result of the complexity of the performance-related requirements that are usually referred to in the design of such mixtures.

Mineral sludge considered in the study came either from stone cutting operations or from the washing of aggregates employed for production of bituminous mixes and Portland cement concrete. In both cases it was found that they were abundantly available and that several issues were present with respect to their potential reuse.

Residual sludge produced during the processing of ornamental stones is considered a waste (EWC code 010413) and according to available statistics its annual production in Europe is equal to approximately 5 million tons [21]. The main challenges for the management of this type of sludge derive from its huge volume, very fine particle size distribution and high water content. Mineral composition of sludge depends on the parent rock, although the most common minerals are feldspars, quartz, calcite and mica [22]. Metals which derive from wear and tear of cutting tools are also present and this prevents the direct reuse of sludge without any treatment or processing because of its potential contaminating effects. As a consequence, in order to fit into the framework defined by the European Commission for the prevention and recycling of waste [23], stone cutting companies have tried to to identify potential industrial applications in which sludge may be employed in immobilized form, mainly by the inclusion in building materials. Significant examples of such attempts are represented by the use of granite cutting sludge in coloured cement mortars [24], in floor tiles [25] and as partial replacement of sand in cement concrete [26]. The use of limited quantities of granite sludge as a Supplementary Cementitious Material (SCM) was also explored and it was shown that it does not alter the morphological features of cement hydration products and can be used for the manufacture of blended cements [27]. Sludge from the marble cutting industry also found its reuse in different applications of interest for the building and tyre industry [28-30].

Sludge derived from the industrial washing of aggregates, which may constitute 20-25% of the output of crushing operations carried out in quarries, is also considered as waste. However, some attempts have been made in order to reuse this type of material as part of specific construction operations. According to data available in literature, in combination with soil it may reach satisfactory California Bearing Ratio (CBR) values and as a consequence may be employed in pavement sub-base layers [31]. Other studies have indicated that quarry dust may have a negative influence on the compressive strength and on other mechanical properties of Portland cement concrete [32]. Finally, it has been found that quarry dust can be used as a raw material in self-compacting concrete in substitution of fly ash and silica fume to reduce the cost of production [33] and as a stabilizing agent in CLSMs [34].

As in the case of RAP, no studies have considered the potential use of mineral sludge in the production of FTBs. However, in the context of the research work presented in this paper it was envisioned that sludge can provide added value to these composites as a result of two main characteristics. On one hand, its fine particle size distribution may be of aid in guaranteeing an adequate flowability to FTBs, improving their stability and preventing segregation and bleeding [35-36]. On the other hand, depending upon its mineralogical composition sludge may contribute to the increase of the thermal conductivity of FTBs. In particular, it should be noted that while water and air have thermal conductivity values equal to 0.6 and 0.024 W/(m·K), respectively, minerals which constitute mineral sludge may have significatly higher values as in the case of quartz (7.69 W/(m·K)), calcite (3.59 W/(m·K)), chlorite (5.19 W/(m·K)) and muscovite (3.48 W/(m·K)) [37].

In the experimental investigation described in this paper the Authors focused on the design and performance assessment of FTBs containing significant quantities of Reclaimed Asphalt Pavement (RAP) and mineral sludges produced by the crushing of mineral aggregates and by the cutting of natural stones. Consistently with the intended end-use of considered FTBs, relevant properties which were measured in the laboratory included flowability, thermal conductivity and thermal stability. The effect of thermal conductivity of the FTBs on the ampacity of a high-voltage transmission line was also discussed.

2 MATERIALS AND METHODS

2.1 FTB components

Aggregates used for the formation of the lithic skeleton of FTBs were obtained from a road construction contractor and were preliminarily characterized by evaluating their particle size distribution and specific gravity (SG) as per corresponding EN standards [38-39]. Employed aggregate fractions included coarse gravel (indicated as 8-18 mm), coarse sand (designated as 0-8 mm) and RAP (preliminarily treated to reduce its maximum particle size to 12.5 mm). Use of RAP was considered to be compatible with the low strength requirements of the FTBs, while it was assumed that its effects on fluidity and thermal properties could be directly assessed during design.

In order for FTBs to exhibit a fluid behavior and achieve a dense state after setting, it is necessary to include in their formulation a relevant amount of fines. In such a context, possible use of three recycled mineral sludges of different types and origin was considered in the study. One sludge, referred to as “aggregate sludge” (AS), was retrieved from the crushing and washing operations of the abovementioned natural aggregates (coarse gravel and coarse sand). The others were obtained as by-products of the cutting and polishing of granite stones in two different plants: depending upon the respective cutting process, they were indicated as “sawmilling sludge - diamond disc” (SS-D) and “sawmilling sludge - frame saw” (SS-F).

At the moment of sampling all sludges were characterized by a very high water content (of the order of 20-30%), but during the preparation of FTBs they were used in their oven-dried state. Preliminary characterization of the sludges was carried out by means of the same procedures employed for aggregate fractions (determination of particle size distribution and specific gravity). Furthermore, since it was expected that sludges would be contaminated due to the wear and tear of crushing, cutting and sieving tools, chemical analyses were performed by means of an ICP (inductively Coupled Plasma) mass analyzer in order to determine their heavy metals and iron content (as per EPA 3051A/2007 and EPA 6020A/2007). Microstructure of the mineral sludges was also characterized by means of Scanning Electron Microscopy (SEM) using FEI model Quanta Inspect 200 LV and Energy Dispersive X-Ray (EDX) using EDAX Genesis with the SUTW detector. In order to identify crystalline phases, mineral sludges were also examined by means of X-Ray powder Diffractometry (XRD) using Rigaku model Geigerflex.

Further component materials employed in the FTBs included cement, belonging to class CEM II/A-L R42.5 as per EN standard [40], potable water, totally exempt from impurities, and a commercially available polycarboxylate-based superplasticizer used to improve fluidity.

Results obtained in the preliminary characterization of component materials are synthesized in Fig. 1 and Table 1, while Table 2 lists the data obtained from the chemical analyses performed on the mineral sludges.

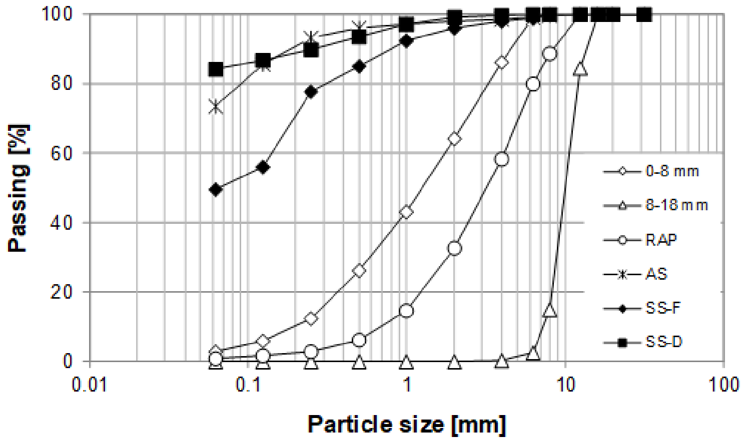

Fig. 1 Particle size distribution of employed aggregates, RAP and mineral sludges

Table 1 Specific gravity of employed components

Fractions	SG
0-8 mm	2.745
8-18 mm	2.733
RAP	2.527
AS	2.785
SS-F	2.954
SS-D	2.666
Portland cement	3.150

Table 2 Chemical composition (heavy metals and iron) of mineral sludges

Sludge	Co [mg/kg]	Ni [mg/kg]	Cu [mg/kg]	Cr tot [mg/kg]	Zn [mg/kg]	Pb [mg/kg]	Fe [%]
AS	23.9	88.7	43.1	143.9	89.7	19.8	27.2
SS-D	20.2	0.4	<0.1	3.0	17.5	28.9	4.1
SS-F	21.3	69.5	96.7	88.0	85.3	17.5	29.9

With respect to the results of sieve analyses, it was found that the RAP material was characterized by a continuous particle size distribution which makes it a good candidate for inclusion in FTBs. Significant differences were recorded when comparing the three sludges. In particular, while sludges AS and SS-D were almost entirely passing the 0.25 mm sieve, sludge SS-F proved to be definitely coarser.

As expected, it was observed that the specific gravity of AS sludge was close to those recorded for the aggregate fractions from which it was derived, while RAP exhibited a relatively low SG value due to the presence of aged bitumen films covering individual particles. Finally, SG values measured on the SS-F and SS-D sludges confirmed their different origin in terms of cutting operations and mineralogical composition.

Differences in the composition and origin of sludges were also reflected by the results of chemical analyses. Given that in standard aggregate processing there is no use of sharp cutting tools it can be hypothesized that metals detected in the AS sample are mainly derived from the parent rock. The SS-D sample showed high concentrations of Co, which is part of the diamond segment used for cutting, while other metals were all found in very low concentrations. The SS-F sample was characterized by higher concentrations of Fe, Cr, Cu and Zn which come from the blades and metal grit used during cutting. Regardless of origin and type, for all sludge samples the concentration of heavy metals was found to be lower than the legal limits defined by Italian legislation for use in industrial and commercial applications [41-43]. In such a context it should be emphasized that when including the considered sludges in FTBs, a reduction of their free leaching potential is also expected due to the immobilizing effect induced on heavy metals by cement stabilization [44- 45].

Results obtained from the detailed microstructural characterization of sludge samples are shown in Fig. 2 (SEM and EDX) and Fig. 3 (XRD). Gathered information was considered as a useful supplement to the simple preliminary characterization illustrated above.

Sludge derived from the washing of quarried aggregates (AS) as investigated by means of SEM revealed a morphology characterized by a sheet-like arrangement of minerals, while the corresponding results from EDX analyses suggests the potential presence of quartz, dolomite, muscovite and chlorite. SEM and EDX results obtained for the diamond disc stone sludge (SS-D) and the frame saw stone sludge (SS-F) indicated the presence of metallic grains, possibly due to the wear and tear of cutting tools. In the specific case of the SS-D sample, obtained results highlight the presence of Co and Cu which derive from the employed diamond cutting tools. In the case of the SS-F sample, the highlighted presence of Fe and Ca are respectively due to the employed cutting tool and to the antioxidant used during this processing.

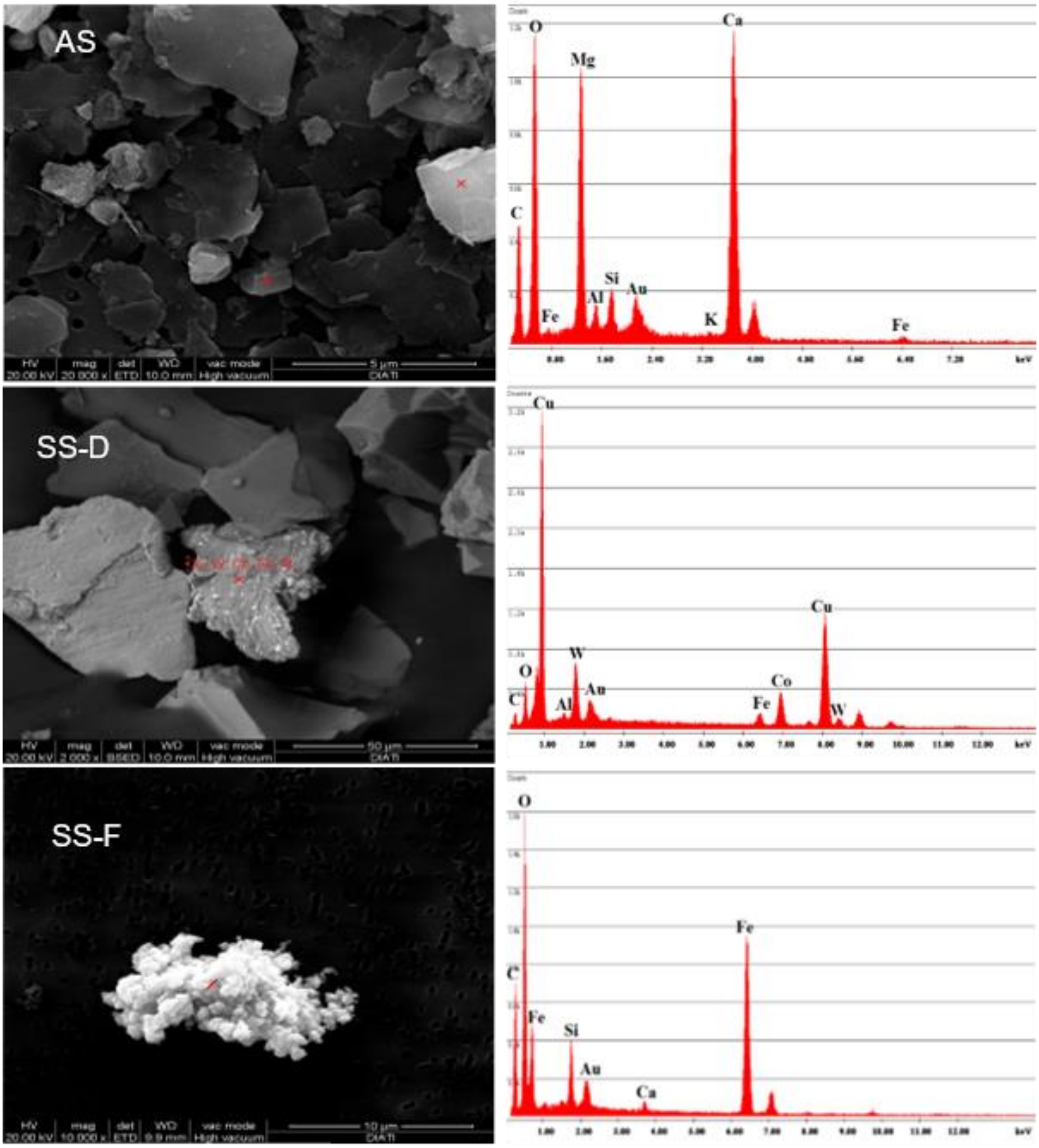

Fig. 2 Results of SEM and EDX analyses performed on sludge samples

XRD peaks identified in the case of the AS sludge were associated to the presence of quartz, calcite, dolomite, chlorite and muscovite, thus confirming the findings coming from the SEM-EDX analyses. Results obtained on the SS-D and SS-F samples showed similar peaks corresponding to quartz, feldspar and mica (not highlighted in Fig. 2), while no peaks associated to metals were identified as a result of their very low quantity.

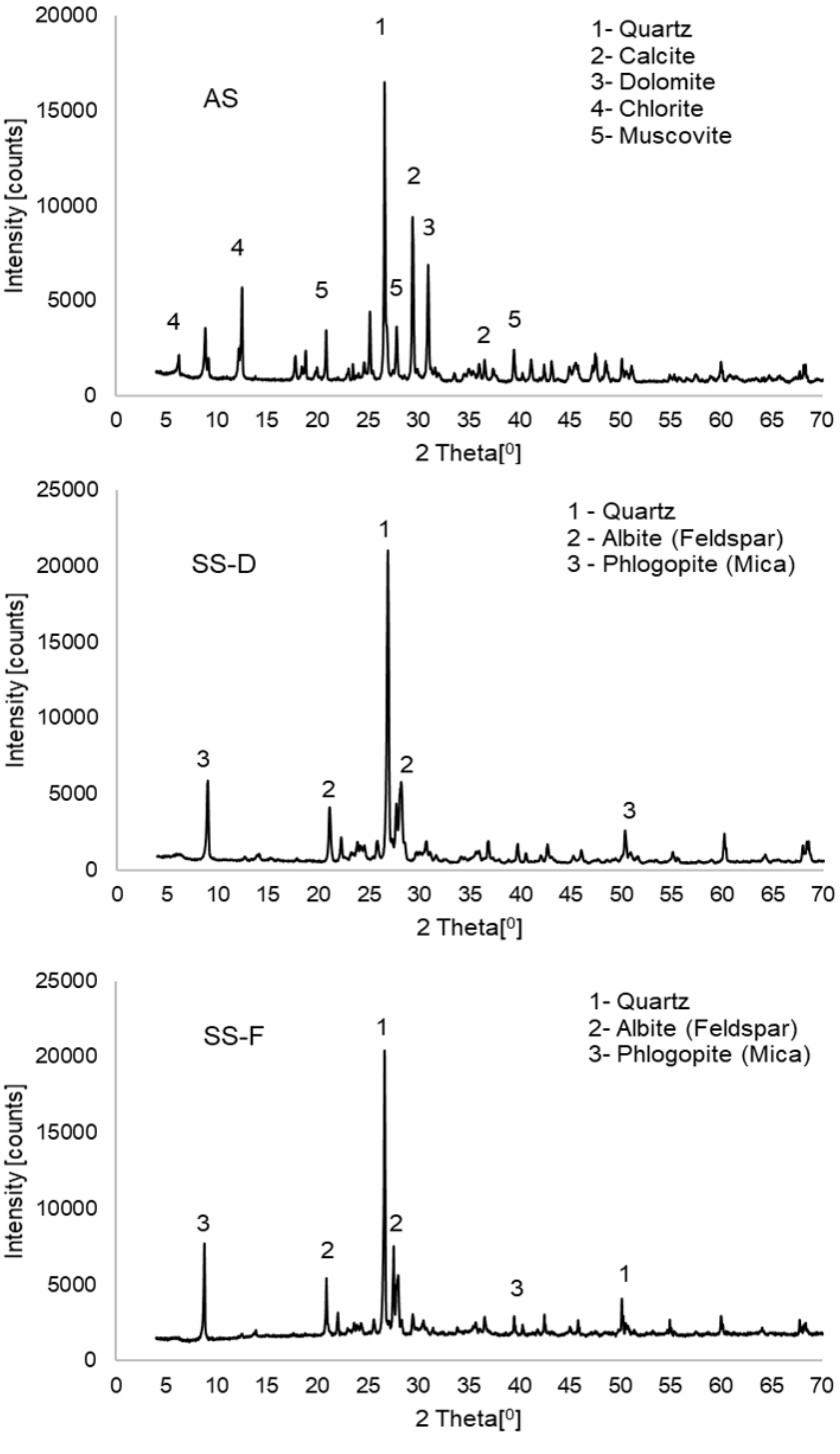

Fig. 3 Results of XRD analyses performed on sludge samples

2.2 FTB mixtures

There is no standard mix design methodology for the design of FTBs. However, it is well recognized that flowability and self-compacting ability of these cement-based composites can be achieved by optimizing the particle packing of the aggregate skeleton and by varying water content [46]. Thus, in the investigation described in this paper, available components were combined in order to yield a total size distribution that would replicate as closely as possible the following target one suggested by Funk and Dinger for self-compacting concrete, known and the “modified Andersen and Andreasen model” [47]:

$$P_D = \frac{D^q - D_{min}^q}{D_{max}^q - D_{min}^q} \cdot 100 \tag{1}$$

where:

P_D is the percentage passing the sieve with opening equal to D (%)

D is diameter of aggregate particles (mm)

D_{min} is the minimum diameter of aggregate particles in the mix (mm)

D_{max} is the maximum diameter of aggregate particles in the mix (mm)

q is the distribution modulus (assumed equal to 0.21 in the investigation)

The target size distribution adopted in the investigation is shown in Fig. 4, where for the same maximum particle size (equal to 16 mm) it is compared to the classical Fuller curve adopted for the design of dense-graded mixes [48].

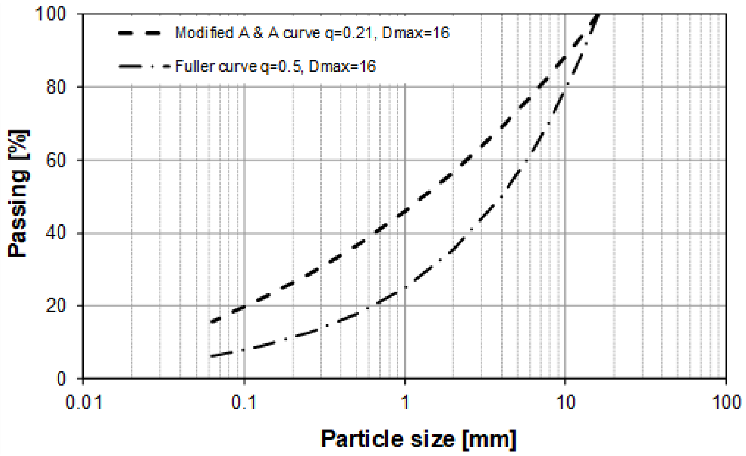

Fig. 4 Target and Fuller particle size distribution

Composition of the laboratory-prepared FTB mixtures included in the investigation was defined by considering, for each type of sludge, variable cement content (equal to 60, 80 and 100 kg/m^3), RAP content (equal to 0, 15, 20 and 30%), and water-to-powder ratio (W/P, equal to 0.70, 0.75 and 0.80). The dosage of superplasticizer was kept equal to 0.5% by weight of cement for all mixtures. The term powder is herein used to collectively indicate cement and sludge, which jointly contribute to paste fluidity and void filling. The full-factorial testing matrix stemming from the combination of the factors indicated above was reduced to a more manageable test plan in which the effects of each variable could still be highlighted. In particular, RAP content was varied only in the case of the FTB mixtures containing sludge AS, while it was fixed at 20% in the case of FTB mixtures containing sludges SS-D and SS-F.

Percentages of the various components constituting the aggregate skeleton of the mixes (virgin aggregates, RAP and sludge) were identified by minimizing the differences between the total particle size distribution and the reference one defined in equation (1). To avoid biasing effects stemming from the combined use of components with different specific gravities, size distributions were expressed in volumetric terms. As indicated in Fig. 5, in all cases the corresponding residual deviations were found to be extremely small.

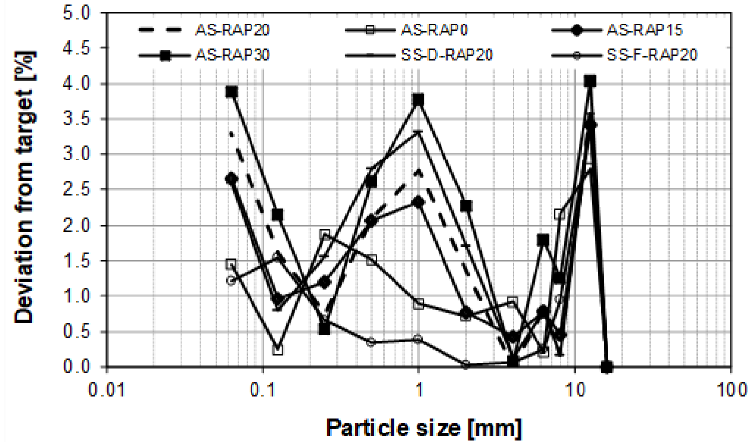

Fig. 5 Residual deviations from target particle size distribution

Table 3 lists the composition of all the FTBs considered in the investigation. They were all prepared by making use of a laboratory mortar mixer and by adopting a protocol which consisted of preliminary mixing of dried aggregates and cement, followed by addition of premixed solutions of water and superplasticizer additive, and completed by continuous mixing until achievement of a homogenous composite.

Table 3 Composition of FTB mixtures

FTB mixture	Cement [kg/m3]	W/P [-]	Composition of aggregate skeleton			
			RAP [%]	Sludge [%]	0-8 mm [%]	8-18 mm [%]
AS-RAP20-C60-0.8	60	0.8	20	24	39	17
AS-RAP20-C80-0.8	80	0.8	20	24	39	17
AS-RAP20-C100-0.8	100	0.8	20	24	39	17
AS-RAP0-C100-0.8	100	0.8	0	21	57	22
AS-RAP15-C100-0.8	100	0.8	15	23	44	18
AS-RAP30-C100-0.8	100	0.8	30	25	31	14
AS-RAP20-C100-0.75	100	0.75	20	24	39	17
AS-RAP20-C100-0.7	100	0.7	20	24	39	17
SS-D-RAP20-C100-0.7	100	0.7	20	23	40	17
SS-D-RAP20-C100-0.8	100	0.8	20	23	40	17
SS-F-RAP20-C100-0.7	100	0.7	20	32	30	18
SS-F-RAP20-C100-0.8	100	0.8	20	32	30	18

Flowability of the investigated mixtures was evaluated by making use of the flow consistency test described in ASTM D 6103 [49]. As prescribed by the standard protocol, an open-ended cylinder of 75 mm diameter and 150 mm height is filled with FTB which is thereafter allowed to spread over a non-absorbent flat surface by lifting the cylinder. The spread diameter (D_s) is then measured and the test sample is visually observed to identify any segregation or bleeding phenomena. It is reported that a flow spread of 170-250 mm can be considered adequate for trench filling applications [12].

Thermal conductivity of the FTBs were measured as per ASTM D 5334 [49] by employing a thermal needle probe (KD2 Pro Thermal Properties Analyzer of Decagon Devices Inc.) which has been extensively used by different researchers for the evaluation of thermal conductivity of soils and cement composites [6, 50-51]. In the present study, thermal conductivity tests were performed on cylindrical specimens 100 mm in diameter and 200 mm in height which were cured at room temperature. Three holes were drilled on the top surface of each specimen before hardening in order to allow the later introduction of the needle probe (100 mm long and 2.4 mm in diameter). To avoid any misreading in measurements, a sufficient free clearance was kept between adjacent holes and between the holes and the lateral specimen surface.

The needle probe acts both as a transient line heating source and as a temperature sensor. Temperature measurements are recorded, at the same intervals, after heating the needle for a fixed duration and during cooling. Thermal conductivity is consequently assessed according to the following equation:

$$k = \frac{q}{4\pi a} \tag{2}$$

where k represents the thermal conductivity (expressed in W/(m·K)), q the heating power of the needle and a indicates the slope of the straight line which models temperature as a function of the logarithm of time.

Tests were carried out at different curing times (7, 14 and 28 days). Furthermore, after 28 days of curing, specimens were oven-dried at 60 °C for 48 hours in order to obtain further thermal conductivity measurements which are believed to be representative of low-moisture conditions which may occur during the service life of FTBs. Such measurement conditions are referred to as "lab-dried".

As a supplement to all the performance-related tests described above, selected analyses were carried out on FTB mixtures by means of SEM and EDX by using the same equipment described in section 2.1.

2.3 Ampacity of high-voltage lines embedded in FTB mixtures

As part of the performance-related evaluation of the FTBs considered in the investigation, calculations were performed in order to assess the ampacity of a reference high-voltage transmission line. Ampacity represents the maximum current-carrying capacity of a line which is defined as a function of the limiting conditions in terms of maximum allowable heating of the cables [52]. Such a heating is affected not only by the line characteristics and configuration, but also by the thermal properties of the employed backfill materials. As discussed in literature, use of properly designed FTBs can enhance the ampacity of the cables as well as reduce the construction time and overall cost due to the assured quality and quick installation [53].

As shown in Fig. 6, the reference high-voltage line considered as a reference consists of a four-cable 320 kV arrangement in which the cable contained in conduits are buried directly in the FTBs without any protective duct banks. The target ampacity of this particular line was considered equal to 600 MW. Since this specific case was referred to a tunnel, air temperature was fixed at 40 °C, while the maximum allowable temperature for the safe operation of cables was set at 70 °C. Ampacity calculations were carried out by making use of the model proposed by Neher and McGrath [54].

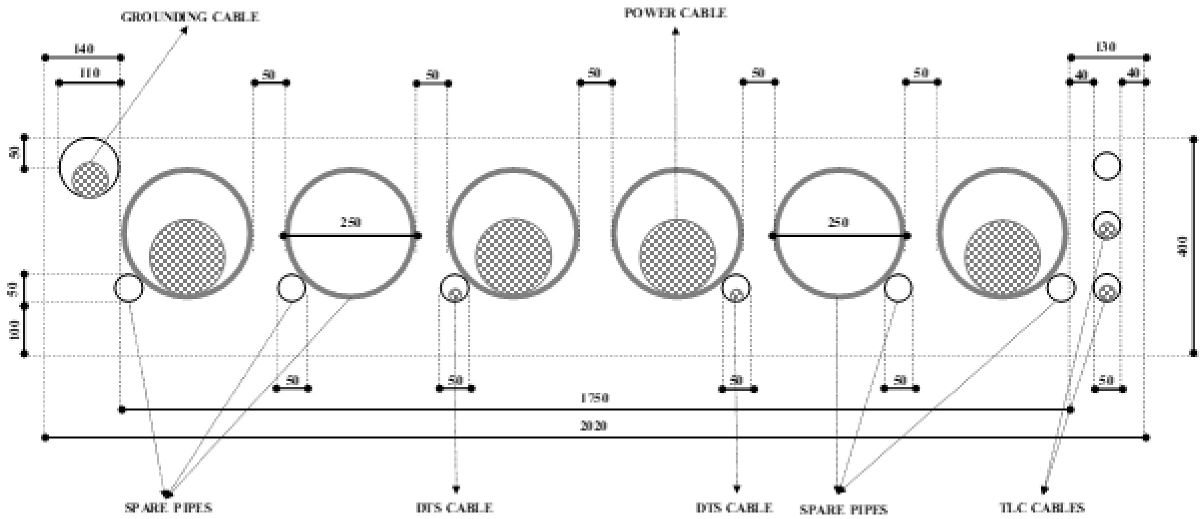

Fig. 6 Reference high-voltage transmission line used for ampacity calculations

3. RESULTS AND DISCUSSION

Experimental results obtained during the investigation are synthesized in Table 4. Spread diameter (D_s) was derived from measurements performed along two orthogonal directions after specimen spreading. Thermal conductivity (k) was calculated as the average of the readings obtained from the three measurements performed on each specimen.

Table 4 Synthesis of experimental results

FTB mixtures	D_s [mm]	k [W/(m·K)] at 7 days	at 14 days	at 28 days	lab-dried
AS-RAP20-C60-0.8	213	1.512	1.627	1.475	0.820
AS-RAP20-C80-0.8	225	1.661	1.662	1.697	1.022
AS-RAP20-C100-0.8	235	1.809	1.865	1.745	1.068
AS-RAP0-C100-0.8	204	1.670	1.549	1.386	0.863
AS-RAP15-C100-0.8	222	1.869	1.775	1.639	1.017
AS-RAP30-C100-0.8	-	-	-	-	-
AS-RAP20-C100-0.75	225	1.609	1.514	1.371	0.902
AS-RAP20-C100-0.7	210	1.632	1.635	1.333	0.864
SS-D-RAP20-C100-0.7	240	1.652	1.519	1.620	0.794
SS-D-RAP20-C100-0.8	-	-	-	-	-
SS-F-RAP20-C100-0.7	260	1.908	1.675	1.450	0.873
SS-F-RAP20-C100-0.8	-	-	-	-	-

As shown in Table 4, all the investigated FTBs exhibited flow spreads greater than 200 mm, thus satisfying the requirements suggested in ACI guidelines [12]. However, bleeding and segregation phenomena occurred in mixtures manufactured with SS-D and SS-F sludges when the W/P ratio reached a value of 0.8, thus preventing the measurement of flow spread. These effects, which probably derive from the specific water absorption properties of employed sludges, do not allow the use of the corresponding FTBs as trench filling materials since a non-homogeneous distribution of air voids and moisture can lead to unacceptable thermal properties. Mixes with 30% RAP also showed similar segregation and bleeding and therefore were not considered in subsequent thermal conductivity analyses.

With respect to thermal conductivity, results were analyzed to identify the effects of variations of curing time, cement content, RAP dosage, W/P ratio and sludge type. Furthermore, results obtained in lab-dried conditions were considered in order to have information on thermal stability.

Fig. 7 shows the results obtained on FTBs prepared with variable cement content and by employing the AS sludge with 20% RAP and W/P equal to 0.8. In agreement with other studies [55-58], it was observed that curing time has a negligible effect on thermal conductivity, probably as a result of the presence of a densely packed aggregate skeleton which results in a low void content. Furthermore, cement content has a significant influence on thermal conductivity, which increases by 20% (passing from 1.475 to 1.745 W/(m·K)) when changing cement content from 60 to 100 kg/m^3. Such a variation is due to the thermal conductivity of the products formed during the hydration process of cement, which is higher than that of water (equal to 0.604 W/(m·K)) and lower than that of dry cement powder (1.55 W/(m·K)) [51]. Moreover, experimental outcomes can also be explained by considering the porosity reduction induced by making use of higher cement dosages [55, 59].

Effects due to other composition variations are represented in Fig. 8, which refers to thermal conductivity measurements carried out on selected sets of FTBs after 28 days of curing. It can thus be noticed that all considered factors may have an impact on the thermal properties of FTBs.

In the case of RAP, observed variations may be attributed to the concurring change in dosage of the other components (such as sludge) and to the associated effect on particle size distribution, porosity and cement paste volume. A 22% difference was observed between the FTB with only virgin aggregates and the one containing 20% RAP (mixtures with 100 kg/m^3 cement, AS sludge and W/P equal to 0.8).

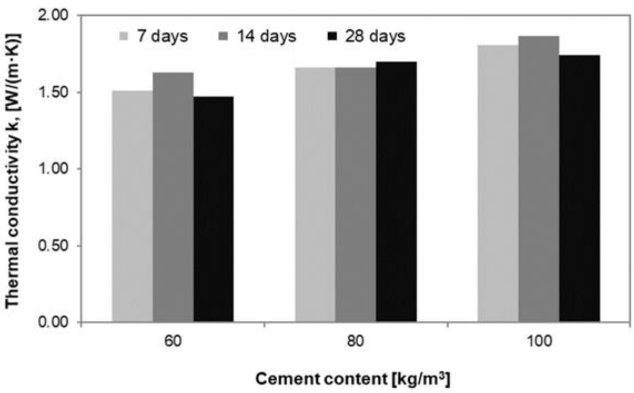

Fig. 7 Effect of cement content and curing time on thermal conductivity

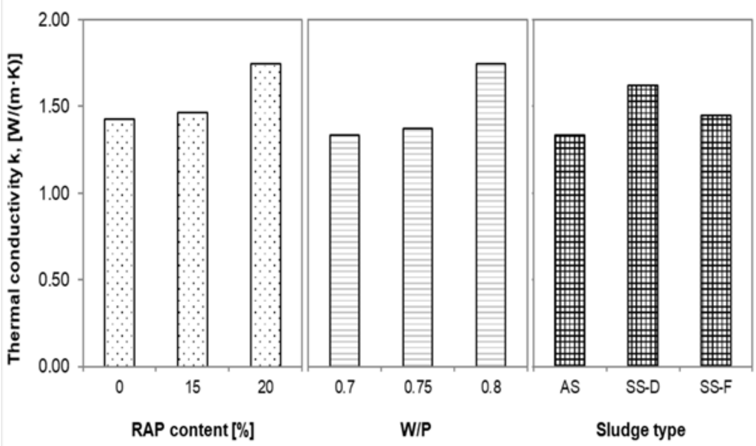

Fig. 8 Effects of composition variations on thermal conductivity

Recorded effects due to W/P variations were also non-negligible. In particular, thermal conductivity increased significantly (by approximately 30%) when W/P reached the highest value considered in the investigation (equal to 0.8, for mixtures prepared with 100 kg/m^3 cement, AS sludge and 20% RAP). Such an occurrence can be explained by considering that water has a higher conductivity than air, and that mixtures characterized by an excess moisture are prone to be highly conductive.

Finally, effects related to variations of sludge type were also apparent as a result of their variable mineralogical and chemical composition (already discussed in section 2.1). In particular, this is shown in Fig. 8 by considering mixtures prepared with 100 kg/m^3 cement, 20% RAP and W/P equal to 0.7.

As mentioned in section 1, thermal stability is an essential requirement of FTBs in the case of buried high-voltage cables which continuously transfer heat to the surrounding backfilling material, causing a progressive reduction of moisture. Thus, in the present study assessment of FTB thermal stability was carried out by comparing thermal conductivity measured in lab-dried conditions to that recorded after 28 days of curing.

In general terms it was observed that the very low moisture content reached in lab-dried conditions led to a significant reduction of thermal conductivity. However, values recorded in these limiting conditions were still compatible with typical design requirements, which indicate 0.8 W/(m·K) as the recommended minimum limit. This is once again due to the dense packing of the aggregate skeleton comprised in the considered FTB mixtures and to the presence of a highly conductive hydrated cement paste.

Examples of the results obtained during the investigation are provided in Fig. 9, which refers to mixtures prepared with variable cement content and by employing the AS sludge with 20% RAP and W/P equal to 0.8. It can be observed that for these mixtures the thermal conductivity reduction was in all cases of the order of 40%.

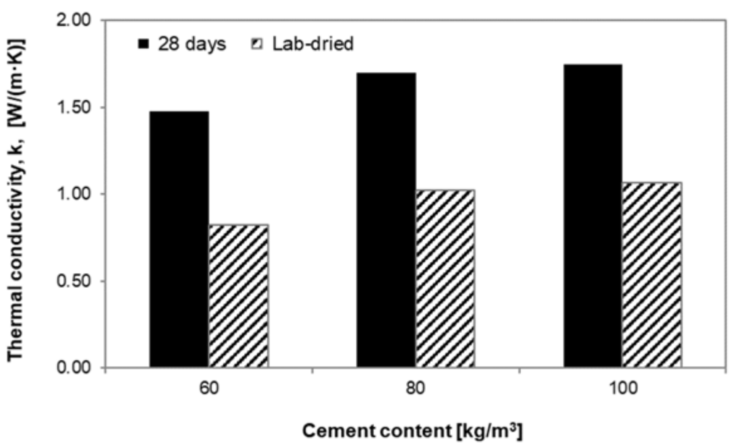

Fig. 9 Thermal stability of selected FTBs

Results obtained from SEM and EDX analyses carried out on FTBs are shown in Fig. 10, which refers to a mixture prepared with AS sludge and 20% RAP. The purpose of the analyses was to verify the immobilization of heavy metals which is a desired effect in the context of waste reutilization in cement-bound composites. Obtained results confirm the expected formation of calcium-silicate-hydrates (CSH), characterized by a poorly crystalline structure with different morphologies, by the presence of impurities such as Al, Mg and Fe, and by a binding affinity towards metals [60]. It was also observed that the microstructure of the prepared FTBs is characterized by void spaces and weak interfaces between aggregates and cement paste. This may be due to the high water content and low cement dosage adopted during the mix design.

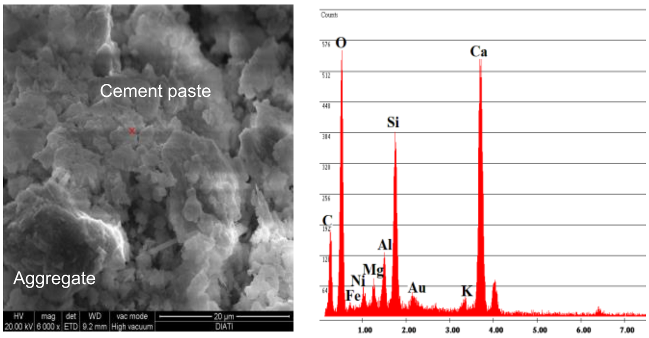

Fig.10 Results of SEM and EDX analyses performed on a selected FTB

The ampacity calculations performed as indicated in section 2.2 were based on the experimental results listed in Table 4, and were carried out in by considering both short-term and long-term conditions. In the first case, thermal conductivity values employed as input data to the Neher and McGrath model were those measured after 7 days of curing. In the second case data used for calculations were those obtained in lab dry conditions in order to account for the dry-out phenomena which take place in materials surrounding high-voltage cables. In both cases the thermal properties were expressed in terms of thermal resistivity (ρ) which by definition is the inverse of thermal conductivity (k).

Table 5 shows required the range of resistivity values considered in calculations in short-term and long-term conditions, together with the calculated ampacity values. In short-term conditions, ampacity was found to be significantly higher than that of the targeted value of 600 MW for the entire range of thermal conductivity measured at the laboratory. In the long term, line ampacity was found to be very close to target with some values below the 600 MW threshold associated to the higher FTB resistivity values.

Table 5 Ampacity calculations

Short- term		**Long- term**	
ρ_{FTB} [K·m/W]	**Ampacity [MW]**	**ρ_{FTB} [K·m/W]**	**Ampacity [MW]**
0.524-0.661	764.9-718.1	0.936-1.220	644.8-588.0

4. CONCLUSIONS

Results of the experimental investigation described in this paper show that Fluidized Thermal Backfills (FTBs) containing significant quantities of recycled materials can be successfully designed by ensuring satisfactory flowability and thermal conductivity properties. Although the design exercise has been performed on a limited set of component materials and mixtures, the Authors believe that obtained results may be of value for other applications and that the observed effects of composition variables should be taken into account in the development of further studies. The mix design procedure described in the paper could be adopted for the future developments of FTBs with other recycled components.

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